AEROSPACE REPORT NO.
ATR-75(7906)-1, VOL. I

EQUIPMENT SYSTEMS IMPROVEMENT PROGRAM

FINAL REPORT

PROTECTIVE ARMOR DEVELOPMENT PROGRAM

Volume I-Executive Summary

DEVELOPMENT

Prepared for

NATIONAL INSTITUTE OF LAW ENFORCEMENT AND CRIMINAL JUSTICE
Law Enforcement Assistance Administration
U.S. Department of Justice

THE AEROSPACE CORPORATION

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PROTECTIVE ARMOR DEVELOPMENT PROGRAM
VOLUME I - EXECUTIVE SUMMARY

Law Enforcement Development Group
THE AEROSPACE CORPORATION
El Segundo, California

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VOLUME I – EXECUTIVE SUMMARY

Approved

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Law Enforcement and Telecommunications Division

ABSTRACT

This report summarizes the results of a multiagency effort, funded by the Law Enforcement Assistance Administration for the development of lightweight, inconspicuous body armor to protect law enforcement personnel. The overall activity included identifying operational requirements, conducting ballistic tests, assessing a variety of candidate materials, performing medical assessments, investigating the mechanics of bullet penetration, and subjecting selected materials to environmental testing.

The program emphasized development of a number of protective garment styles, namely, undershirts, sport jackets, and uniform components. Prototype garments were produced and successfully tested for wearability. These garments weigh less than half that of commercially available nylon protective garments and are capable of stopping a .38 caliber bullet fired at close range. The initial test results indicate that such lightweight protective garments can be worn for routine patrol operations during most of the year.

Plans are also discussed for extensive field tests of a variety of these garments under a wide range of field conditions.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ACKNOWLEDGMENTS

This report on the development phase of the Protective Armor program was made possible by the contribution of many agencies and many individuals too numerous to itemize here. Particular contributions were made by the Mitre Corporation, National Bureau of Standards, U.S. Army's Edgewood Arsenal and Natick Laboratory, Lawrence Livermore Laboratory, DuPont, independent consultants, various armor and garment manufacturers, numerous police departments, and several federal agencies. The efforts were funded and directed by the National Institute of Law Enforcement and Criminal Justice with appreciated direction specifically supplied by Messrs. Joe Kochanski, George Shollenberger, and Lester Shubin of the Institute. Dr. John Benfield of UCLA Medical School was an extremely valuable medical consultant to The Aerospace Corporation.

Appreciation is also expressed to the personnel of the Material Science Laboratory of The Aerospace Corporation and consultant Dr. Paul Blatz who performed much of the independent research and experimental test work reported herein.

CHAPTER I. INTRODUCTION

As part of its Equipment Systems Improvement Program, the National Institute of Law Enforcement and Criminal Justice (NILECJ) of the Law Enforcement Assistance Administration (LEAA) initiated a program in FY 1973 to determine the feasibility of developing lightweight, protective garments for use by law enforcement agencies. The overall program objectives were:

- To develop comfortable, inconspicuous, lightweight protective garments capable of providing protection against common handguns
- To demonstrate adequate user protection and acceptance
- To disseminate the technology acquired to both users and industry

The various organizations participating in the program included:

Advanced Technology Division (NILECJ) — overall program control and management.

MITRE Corporation — preliminary operational requirements and supporting operational analyses.

National Bureau of Standards — specifications, standards, test procedures, anthropomorphic data, and industry/user guidelines.

U.S. Army Laboratories (Edgewood Arsenal and Natick) — detailed material, ballistic, and medical testing; garment development.

The Aerospace Corporation — program technical integration, direction of development subcontractors, laboratory testing, field evaluation.

In addition, industry supported yarn development, weaving of the cloth, and designing and fabricating the garments. Also, various law enforcement agencies offered garment and style recommendations and participated in prototype garment wearability tests.

The program consisted of two phases. The initial phase addressed the feasibility of developing improved, lightweight protective garments and included a preliminary threat assessment, ballistic tests for penetration protection, and an initial evaluation of the damage to the body behind protective armor -- "blunt trauma."

The second phase was initiated in FY 1974 and was devoted to developing and testing a variety of protective garments, additional blunt trauma investigation, and laboratory studies of the ballistic protection process. The schedule of the second phase activities and the participants involved are shown in Figure 1.

The results of this program are presented in three volumes:

- Volume I. Executive Summary
- Volume II. Technical Results and Discussion
- Volume III. Appendices

A companion report on the details of the program support provided by the U.S. Army laboratories is being published by that agency.

This document, Volume I, briefly describes the progress and current status of the program.

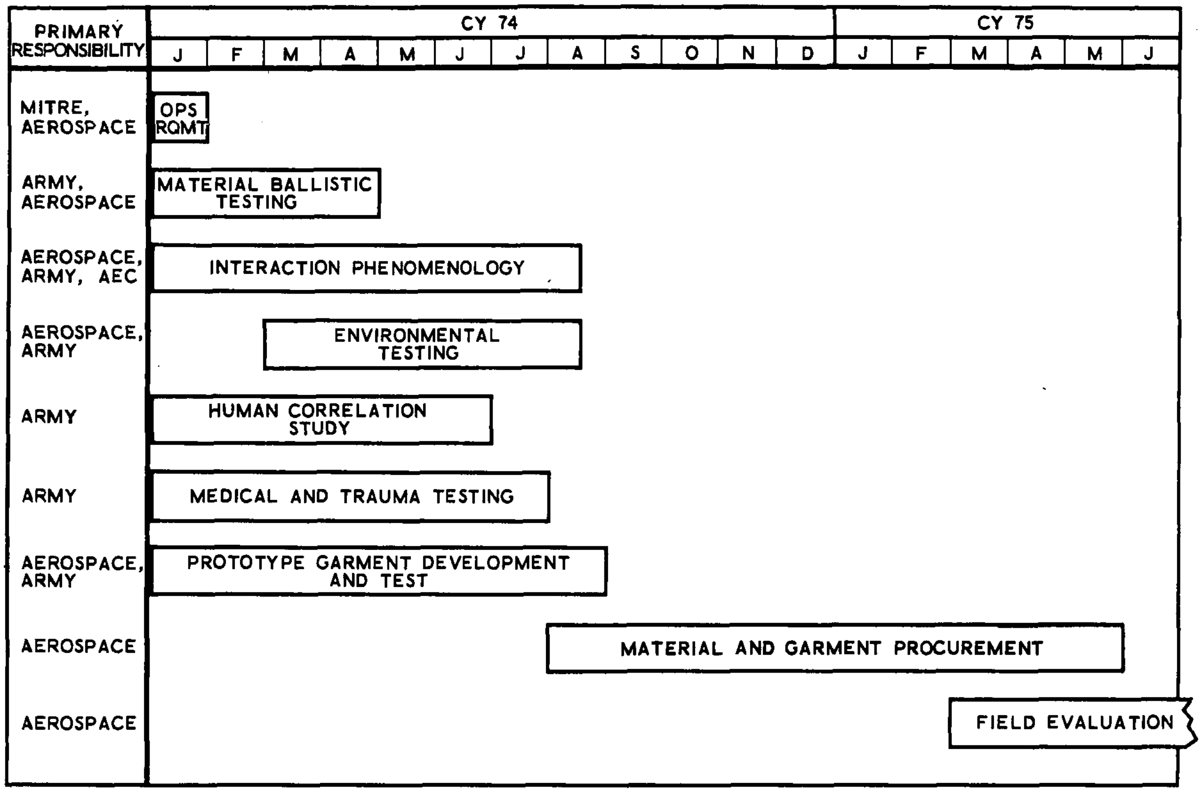


Figure 1. Development and Test Schedule

CHAPTER II. OPERATIONAL REQUIREMENTS

Since 1960 the number of fatalities and serious injuries among law enforcement personnel caused by guns has increased about 15% each year. Approximately 1000 officers and a number of public figures have been shot and killed during this period. Many of the law enforcement fatalities occurred unexpectedly and could have been prevented if appropriate body armor protection had been available and used during routine patrol operations.

Commercially available body armor had, in general, been developed for military use and subsequently adapted to civilian applications. It was usually heavy and conspicuous and was, therefore, often not worn unless immediate danger is anticipated. A recognized need exists for inconspicuous, flexible, lightweight, and relatively inexpensive protective garments for use by law enforcement personnel and public figures

Operational requirements for such garments were determined by assessing the predominent threat and the general operational environment in which such garments are to be deployed. Data on assaults on police were obtained from such sources as the FBI Uniform Crime Reports, the International Association of Chiefs of Police, and individual cities such as Detroit, Atlanta, Chicago, and New York.

A. Assault Survey

The growth of police assault fatalities since 1960 is presented in Figure 2. The trend is of great concern, especially to cities with a population

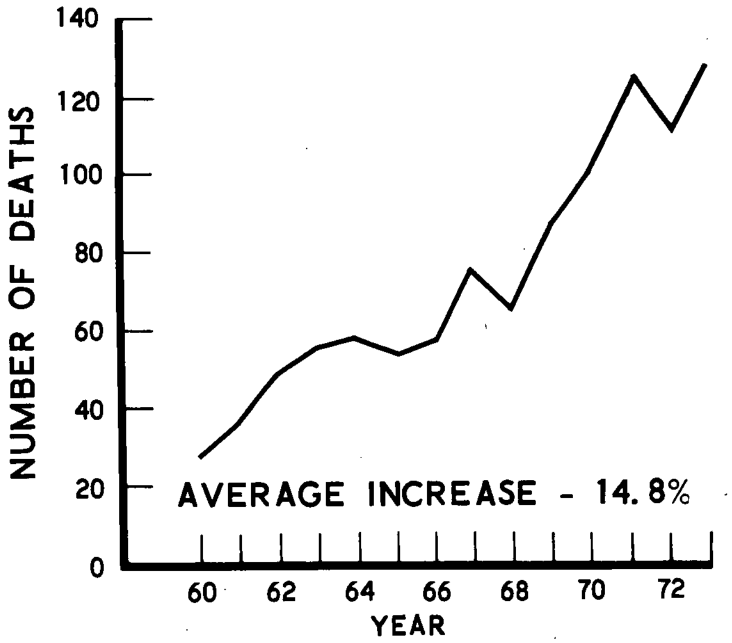


Figure 2. Historical Growth of Police Assault Fatalities (Based on FBI Uniform Crime Reports)

greater than 250,000. Their assault rate is highest, and 1 out of every 125 officers was injured with either a firearm or a cutting instrument during 1972 (according to the FBI Uniform Crime Reports). Of further concern is that over 95% of the law enforcement officers killed during the past decade were shot and that over 71% of all fatalities were caused by handguns. Approximately 40% of the firearm fatalities were from head wounds; 60% were from torso wounds.

B. <u>Firearm Threat Characteristics</u>

An analysis of firearms confiscated during 1973 in a typical large city is shown in Figure 3 and reveals that approximately 65% were in the .38 special or smaller (.38, .32, .25, and .22 caliber) handgun category, about 6% were higher-powered handguns (9 mm, .357 and .44 Magnum), 17% were shotguns, and 12% were rifles. Federal Bureau of Investigation fatality data for 1971 and 1972 indicate that 54% of all police fatalities resulted from common handguns (.38 caliber or less) and 27% from shotguns and rifles. It is clearly apparent that effective protection against the .38 special and smaller handguns should significantly reduce police firearm injuries and fatalities.

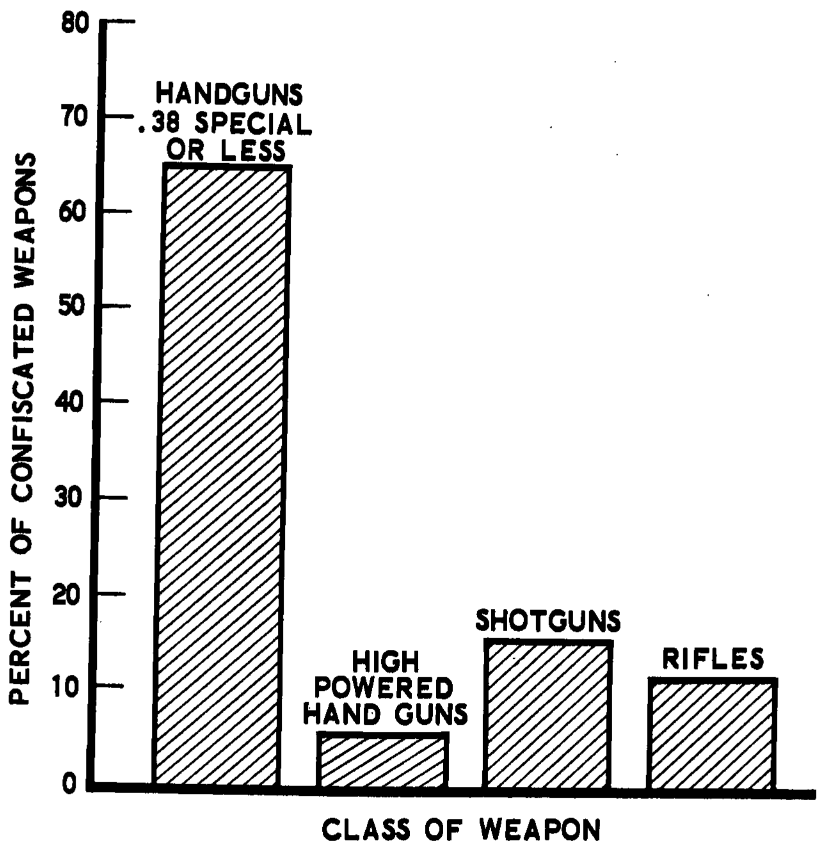


Figure 3. Typical Distribution of Weapons Confiscated by Police -- 1973

C. Requirements Summary

As a result of assessing the statistics assembled and described in the previous sections, the following operational requirements were specified for the protective garment developments initiated under this program:

- The garment should be inconspicuous to the casual observer.
- The garment should not hinder the wearer's performance of his assigned duties nor access to his weapon.
- The garment protection should not be degraded by use and exposure to the operational environment.
- The garment should prevent penetration of a .22 caliber, 40 grain ballistic projectile at 1000 feet per second and also protect against penetration and blunt trauma of a .38 caliber, 158 grain projectile at 800 feet per second.
- The blunt trauma response should not prevent the wearer from immediately defending himself nor should it result in any permanent injury.

CHAPTER III. DEVELOPMENT TESTING

When protective armor is worn, the dissipation of the kinetic energy of a bullet is divided among three separate phenomena: bullet deformation, interaction with and deformation of the protective armor, and interaction with and deformation of the body of the wearer. To properly design lightweight body armor, it is important to understand these phenomena, particularly how they are influenced by various garment design parameters.

With "soft" body armor, stopping the bullet motion is accompanied by a relatively large deformation of the protecting material. This deformation is transmitted to the body which, in turn, also absorbs energy by deformation. If skin tolerance is exceeded, a contusion on the skin surface will result; if the deformation is sufficiently rapid and deep, damage to internal organs may occur. This damage to the body behind protective armor is termed "blunt trauma," and the amount of blunt trauma the body can absorb determines how flexible and lightweight the armor can be made.

The factors that must be considered in evaluating the effectiveness of protective body armor are identified in Figure 4. A major technical effort undertaken as part of this program was assessing the interaction of these factors in absorbing the kinetic energy and momentum of the bullet and preventing penetration and a serious medical injury. Analytic and experimental activities were undertaken as part of the effort to identify and assess the critical body armor design parameters.

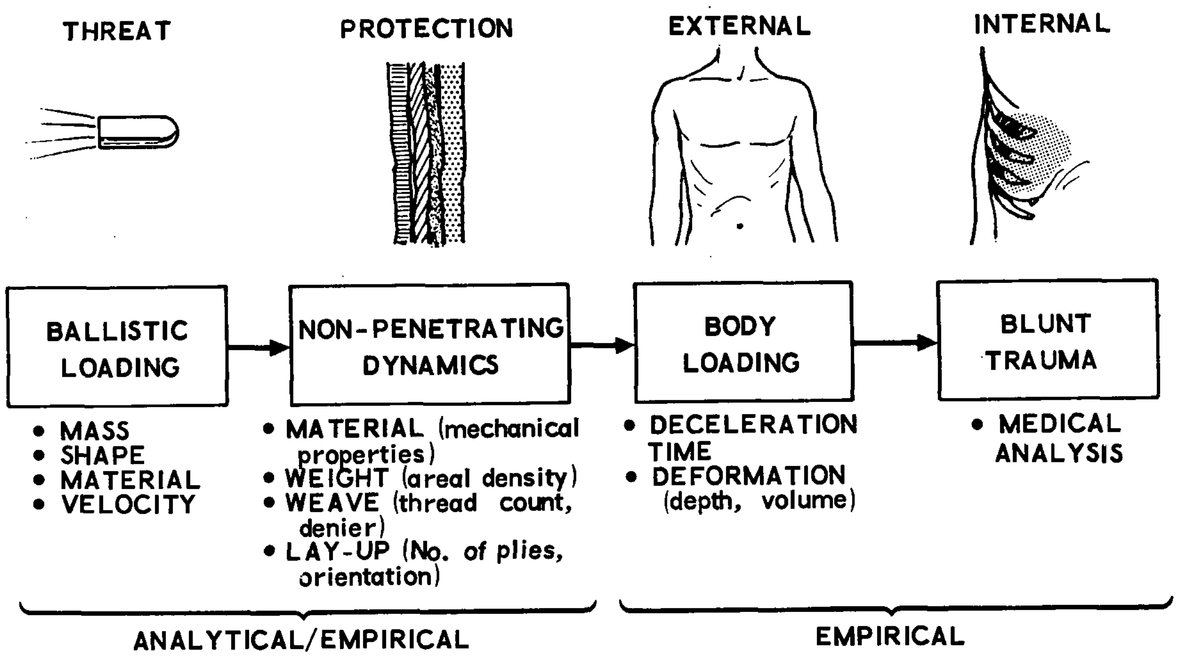


Figure 4. Factors Involved in Establishing Body Armor Effectiveness

A. <u>Material Assessment and Selection</u>

The U.S. Army Textile Research Section, Natick Laboratory, Massachusetts, provided data used in the preliminary selection of candidate materials. The material selection criteria included:

- Weight-to-strength ratio — lightweight but sufficiently strong to prevent bullet penetration
- Fabric flexibility — allows wearer freedom of movement
- Inexpensive — acceptable for extensive procurement for law enforcement applications
- Tailoring feasibility — capable of being tailored into garments with inconspicuous fit and styling

Forty specimens of 12 types of fabric (including nylon, rayon, boron, graphite, and Kevlar) with a range of yarn and weaving types were ballistically tested at Edgewood Arsenal, Kevlar 29, a DuPont synthetic originally developed for use as a tire cord material, was ultimately selected as being most promising for the intended application.

The properties of Kevlar 29 yarn that influence its utility as a protective garment material are given in Table 1. This yarn combines a very high strength and low elasticity with light weight and excellent toughness. Moreover, it is available as a continuous filament yarn in a range of deniers and types for numerous other industrial applications.

Table 1. Physical Properties of Kevlar 29 Yarn

Parameter	Property	Comment
Density	1.45 g/cc	Forty percent less than glass or boron
Tensile Strength	400,000 psi	Substantially above conventional organic fibers, greater than steel
Modulus	19×16^6 psi	Twice that of glass fibers
Chemical Resistance	Good	Resistant to solvents, fuels and lubricants; can not be dyed
Temperature Resistance and Flammability	Excellent	No degradation in short-term exposures to 500°F, self-extinguishing
Textile Processibility	Excellent	Readily woven on conventional looms

B. Ballistic Testing of Kevlar 29 Fabric

Ballistic testing of Kevlar 29 fabric samples was conducted by both the U.S. Army Edgewood Arsenal and The Aerospace Corporation. Aerospace used the facilities of Sierra Engineering Company in El Monte, California and support was also obtained from the Atomic Energy Commission's Lawrence Livermore Laboratory.

Initial in-house Aerospace tests were devoted to rapidly screening a range of deniers, weaves, plies, thread twist, and fabric composites to support definition of Kevlar fabric weaving specifications. These preliminary tests were complemented by more comprehensive ballistic testing at Edgewood Arsenal to identify the baseline ballistic protection provided by each sample. The criteria of merit were whether or not the bullet penetrated the test sample, the degree of bullet deformation, and the size of the cavity in the backing material. It was concluded that a fabric made of 400 denier double-twisted yarn in a 36 × 36 pics (yarns) per inch plain weave had acceptable protection properties and would also be acceptable as the baseline garment material. Subsequent tests near the end of the program suggest that a 1000 denier, single-filament yarn fabric in a 31 × 31 pics per inch plain weave provides at least equivalent protection at a lower material cost.

The results of a typical successful ballistic test of Kevlar is illustrated in Figure 5. Although a depression is created in the fabric, bullet penetration is resisted. Deformation of the bullet with the weave pattern impressed on the blunted foresection is clearly apparent. The degree of bullet deformation depends upon the material denier, the tightness of the weave, the number of plies, and the backing material.

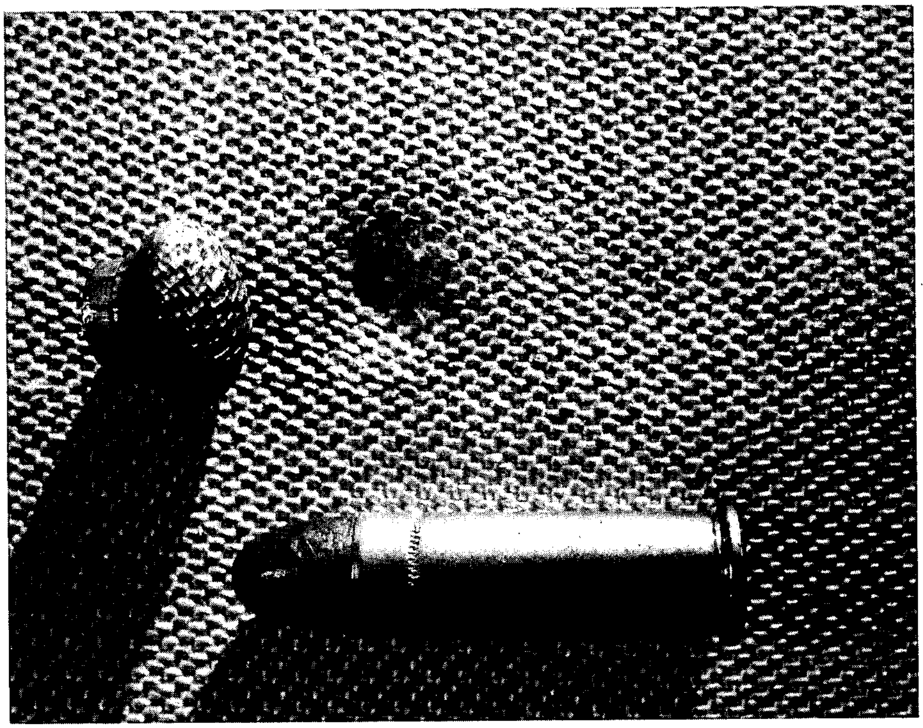


Figure 5. Specimen Material Ballistic Test

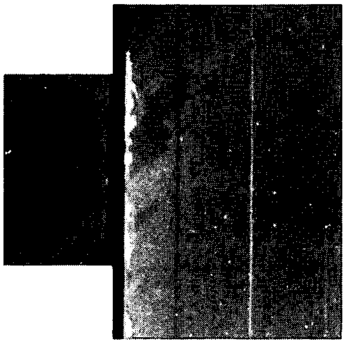
Various backing materials were used in the program, including animal, clay, and gelatin backings, each providing specific information. Animal backing provides medical information, clay backing provides a permanent measure of the energy absorbed by the backing, and gelatin backing permits obtaining high-speed photographs of the time-dependent deformation of the protective material and the backing.

Complementary baseline ballistic tests were performed by the Edgewood Arsenal Biophysics Laboratory and the Lawrence Livermore Laboratory on the backface signature trends (i.e., volume of deformation, depth of penetration, and duration of deformation). The tests covered a range of independent parameters such as bullet energy, material denier and ply, and armor standoff distance from the backing.

Typical results obtained during the backface signature tests are indicated in Figure 6. High-speed photographs, Figure 6(a), show the development of the backface cavity in gelatin backing when penetration is prevented. Increasing the projectile striking velocity generally increases the size of the depression, except for the case of small caliber projectiles which have a tendency to slip through a coarse weave and penetrate the protecting armor.

A backface deformation parameter is used as a relative measure of the intensity of the backface signature. The effect of the number of plies used in the protective garment on this parameter is illustrated in Figure 6(b). The deformation with a .22 caliber bullet is considerably less than that with a .38 caliber bullet, due primarily to the lower energy in the .22 bullet. Nevertheless, both show similar trends with an increase in the number of plies.

This type of testing provided experimental inputs needed to guide the design of the protective garments with respect to the number of plies or fabric layers required to prevent bullet penetration and to minimize blunt trauma. For example, it appears that an increase beyond six to eight layers



t = 20 microsec

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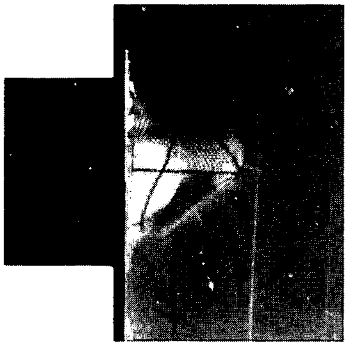
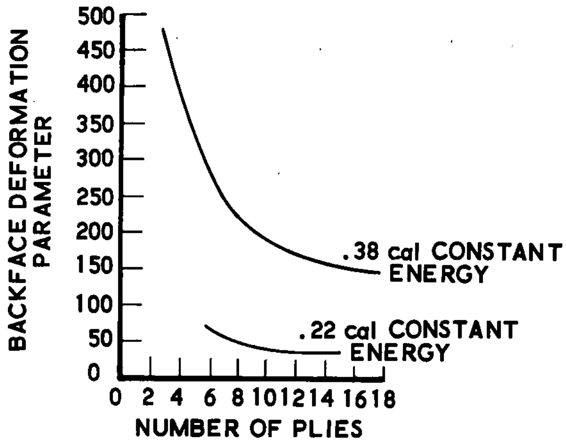


t = 500 microsec

t = 1000 microsec

(a) High-speed photographs of backface cavity development (.38 caliber bullet, Kevlar material, gelatin backing)



(b) Effect of number of plies on backface deformation

Figure 6. Representative Ballistic Test Results

(the level at which there was neither .22 nor .38 caliber penetration) offers less additional blunt trauma protection per ply.

C. Mechanics of Ballistic Protection

A variety of additional analytic and experimental laboratory activities were undertaken to complement the ballistic protection tests discussed in the previous section. The primary purpose was to improve the understanding of the physical interaction among bullet, soft armor, and backing material during a ballistic encounter and lead to fabric and garment design improvements. Three basic types of tests were used:

- Uniaxial tensile tests - to determine the material (Kevlar cloth) structural characteristics in the warp, fill, and bias directions.
- Static indentation tests - to measure the biaxial response of the fabric to bullet shape and steady-state loading forces.
- Dynamic indentation tests - to study the effect of dynamic loading on the interaction and deformation of the material and backing under precise and controlled conditions.

The results of tensile and static indentation tests shown in Figures 7 and 8 provided insight on how the bullet penetrates Kevlar fabric and on possibilities for improving the weave as a means for achieving increased protection. The present weaving process produces fabric in which the warp yarns are highly crimped relative to the fill yarns (i.e., the warp yarns loop over and under the relatively straight fill yarns). As a result, when the fabric is deformed, the fill yarns are stressed much sooner than the warp

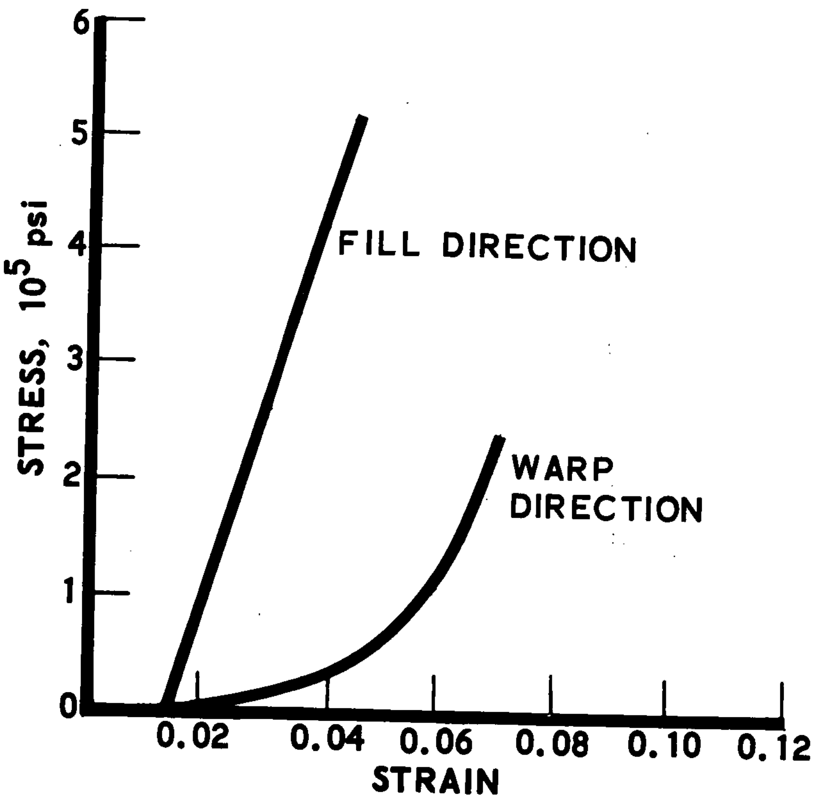


Figure 7. Tensile Test Results for Kevlar Fabric

yarns. Thus, failure is first initiated in the fill yarns. A fabric having the tension forces in warp and fill yarns more equally balanced should result in a more uniform and more effective distribution of stresses.

Dynamic indentation tests were useful for providing insight into the energy transmitted through the protective fabric and into the backing material. Since the energy absorbed in the plastic deformation of the lead bullet is less than 10% of its total energy, the rest must be absorbed in

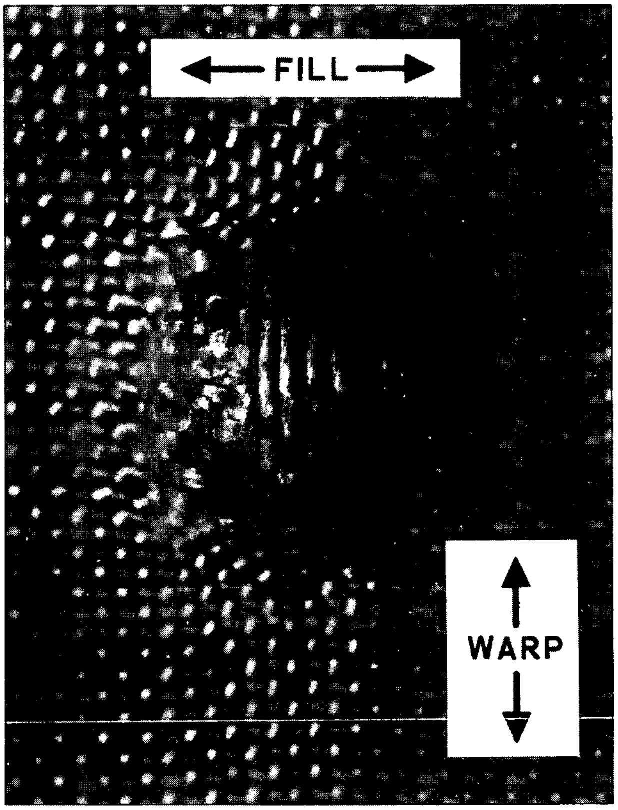


Figure 8. Incipient Penetration of Kevlar Fabric Under Laboratory Impact Loading

stretching the protective fabric, deforming the body of the wearer, and imparting backward motion to the wearer. The function of the protective material is obviously to prevent bullet penetration and to simultaneously distribute its residual energy over as large a surface of the backing material (the body) as is possible. The magnitude of this residual energy and the extent of its distribution is to a degree dependent upon the backing material itself.

The dynamic indentation tests were performed with several backing materials, and the loading energy at which fabric penetration initially occurred was established as a function of the number of plies of protective fabric, Figure 9. With air as the backing material, most of the residual energy is absorbed by the protective fabric and penetration occurred at low energy levels. Clay, on the other hand, deforms plastically and provides a much greater level of energy absorption. Gelatin simulates human tissue better than either air or clay, deforms elastically, and exhibits energy absorption characteristics between air and clay.

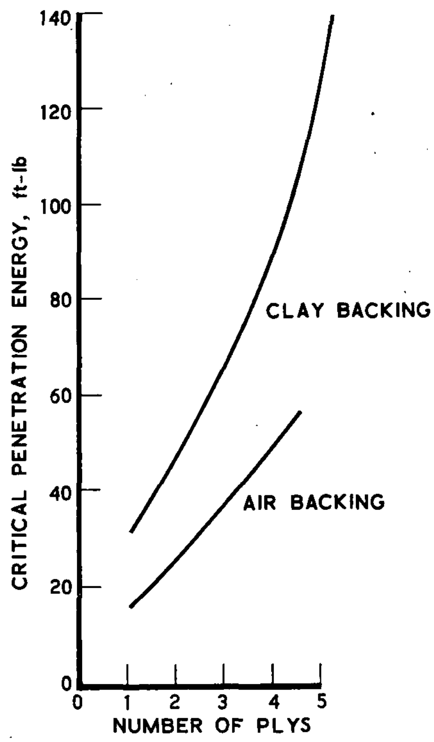


Figure 9. Effect of Backing Material and Number of Plies on Penetration Energy for Kevlar Fabric

The insight acquired from these laboratory tests provided important guidance for improved fabric development and for achieving more effective ballistic protection.

D. Blunt Trauma Evaluation

1. Blunt trauma correlation. Body wall and underlying viscera deformation which occur following nonpenetrating bullet impact represent a major consideration influencing the use of soft body armor. Neither experimental nor analytic techniques for backface simulation of the human body are, as yet, available. Consequently, current assessment of blunt trauma is essentially dependent upon qualitative experimental results.

Under interagency agreement, the Edgewood Arsenal Biomedical Laboratory undertook assessment of the blunt trauma effects with soft body armor. Data from Army sources and published literature for projectile-induced blunt trauma on animals and humans were examined and evaluated. It was concluded that with a protective garment, survival probability after a random hit with a .38 caliber bullet would exceed 95%. It was further concluded that the probability of needing surgery, which exceeds 80% without the garment, is reduced to less than 10% when a protective garment is worn.

Detailed results on this effort and the results on all other U.S. Army support on this program are being reported separately by the U.S. Army.

2. Additional data — actual assaults on protected officers. During mid-1974, three California officers were shot with handguns in separate incidents while wearing commercially available vests of 18-ply ballistic nylon.

All three of these cases were investigated immediately by Aerospace development engineers and a medical consultant. One was shot in the chest area with a .32 caliber automatic and the others were shot in the chest area with .38 specials. In all three cases there was high probability that the wound would have been fatal without the protective garment. Instead, each officer was immediately able to defend himself, returning the gunfire in two of the three cases. The blunt trauma wound behind the point of impact was similar in all three cases, namely, an abrasion which developed into a 2- to 3-inch bruise.

Subsequent to the assaults, samples of the nylon material used in the protective vests involved in these incidents were obtained and subjected to ballistic tests simulating the actual assault conditions. These results were compared to identical tests of Kevlar fabric, and it was concluded that seven plies of Kevlar offered essentially the same penetration protection at about one quarter the weight. A valid blunt trauma comparison could not be made.

E. Environmental Testing of Kevlar 29 Fabric

Since virtually no information regarding the effect of environmental exposure on woven Kevlar 29 was available, Aerospace initiated a brief test program prior to distributing prototype garments to police for wearability testing (discussed in Chapter IV.B). The effects on the fabric of laundering, dry cleaning, ozone, salt water, and humidity were investigated.

Ballistic and mechanical (tensile strength) testing revealed that dry cleaning solvents, household bleaches, and certain detergents significantly degrade the material. As a result, it was recommended that the fabric be washed only in cold-water Woolite or Ivory soap, both of which showed minimal material degradation. For dry cleaning, perchloroethylene, a cleaner used with lightweight knitted fabrics, is recommended.

Although exposure to 100% humidity did not degrade the ballistic protection of Kevlar fabric, degradation did occur by physically wetting the fabric. This appears to be due to a surface effect on the yarns, rather than an actual loss of strength; the moisture acts as a lubricant and aids projectile penetration. When freed of the moisture, the original ballistic protection capability returns. Coating the fabric with a moisture barrier, such as Zepel (a commercial waterproofing chemical), appeared to solve the problem.

CHAPTER IV. GARMENT EVALUATION

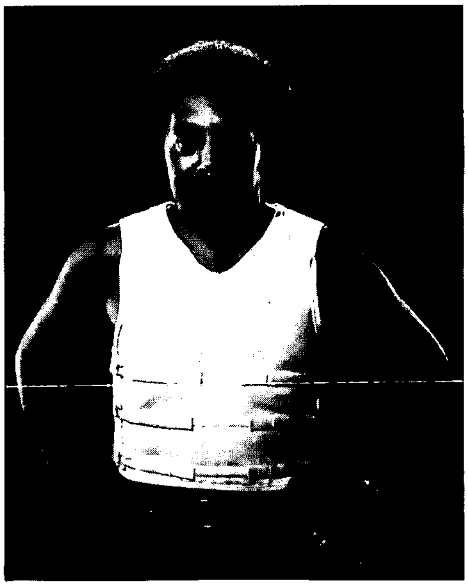
Visual inspection of early samples of woven Kevlar fabric revealed inadequate quality control during the weaving operation. The Aerospace Corporation, in conjunction with DuPont and the U.S. Army Natick Laboratory, produced a weaving specification incorporating visual and mechanical inspection techniques to ensure consistent quality control. For improved ballistic protection, a tight, plain weave was also specified. Based upon these revised specifications, cloth was procured for fabrication into prototype protective garments.

A. Garment Development

Several manufacturers and Natick Laboratory personnel were consulted on Kevlar garment fabrication concepts. Although the material is somewhat difficult to cut and sew, no major fabrication problems were encountered. Various styles of protective garments were produced that were acceptable to the police agencies participating in the wearability tests. The three basic garment types shown in Figure 10 were developed, namely, undershirts, civilian garments, and police uniforms. The uniforms included a variety of jackets and coats made of leather, vinyl, and fabric outer shells with Kevlar inner liners. Civilian garments included sport jacket, dress vest, and slip-over vest designs.

The undershirt was the most universally applicable of all the prototype garments and several design iterations were performed to improve its comfort and wearability. Especially useful during this design phase were

INTEGRATED POLICE UNIFORM



UNDERSHIRT

CIVILIAN GARMENT

Figure 10. Prototype Protective Garments

measurements by Natick Laboratory personnel of the anatomical loads imposed on the wearer. Forces on the wearer while performing a variety of psychomotor tasks such as sitting, stooping, stretching, kneeling, and the reaching for and firing of weapons were measured for the undershirt and other preliminary protective garment designs. These data were then used in conjunction with the wearability test data to improve the garment design.

B. Preliminary Wearability Tests

After consultation with representative law enforcement agencies concerning their interest in participating in a preliminary wearability test program, four test site locations were selected. Test garment selection was based on participant inputs and resulted in the fabrication of 75 garments representing 15 different garment types.

The wearability tests were conducted between April and September 1974 in New York City; Columbus, Georgia; Jacksonville, Florida; and Inglewood, California. Since the weather was generally hot and often humid, some of the winter uniform garments were not evaluated. In general, the undershirt was the most accepted garment, although the outer vests were worn occassionally and were also well received. Negative observations were offered on garment heat containment and some tendency to ride up on the wearer. There were only mild complaints of hindrances to movement and weapon access. In the stress situation of subduing a suspect, the garments did not interfere with the performance of the officers' duties.

CHAPTER V. PLANNED FIELD EVALUATION

Current plans call for initiating a comprehensive protective garment field test program in the spring of 1975. The objectives of this field evaluation include:

- Assessing user acceptance of a continuous-wear protective garment
- Obtaining data on the wear characteristics of protective garments
- Obtaining data on test garment performance
- Obtaining data on cost-effective production of protective garments

Fifteen cities have agreed to serve as participants. It is anticipated that up to 4000 garments will be required for this program. Procurement actions are under way for 15,000 yards of Kevlar cloth, 3000 undershirts, and a variety of other police uniform components and special purpose garments.

Based on preliminary wearability test results, several design changes were incorporated in the protective garment designs scheduled for field evaluation. In addition, the experience acquired during the preliminary wearability tests resulted in the incorporation of the following features in the field evaluation program:

- A special test coordinator from each participating police agency
- Individual fitting of the garments

- Wearer orientation on the garment test program
- Demonstration of protective garment capability to each wearer

CHAPTER VI. CONCLUSIONS

The protective armor program accomplishments have resulted in the following conclusions:

- The common handgun (.22 through .38 caliber) is the greatest threat to law enforcement personnel.
- A relatively inconspicuous, continuous wear, limited protection garment would find extensive application.
- Kevlar, a new lightweight synthetic material, offers protection superior to ballistic nylon. It can be incorporated into a wide variety of inconspicuous protective garments including undershirts, police uniforms, vests, and sport jackets.
- Seven plies of 400 denier Kevlar fabric in a plain weave of 36 pics per inch in both the warp and fill directions provide common handgun protection at less than half the weight of nylon. A 1000 denier weave may offer even better capability and at lower cost.
- The qualities of Kevlar yarn can be better utilized by modifying current weaving techniques to equalize the tension in the warp and fill directions.
- Although some styling modifications may be required, preliminary wear tests indicated user acceptability of Kevlar protective garments with the undershirt the most applicable garment.

CHAPTER VII. RECOMMENDATIONS

Current emphasis has been to demonstrate the ballistic protection capability of garment materials. Future effort should be directed toward:

- Raising the level of protection to include 9mm and .357 Magnum handguns for anticipated threat increases
- Raising the ballistic penetration resistance by improvement in material characteristics, weaving techniques, and ply lay-up while maintaining low garment weight
- Reducing the blunt trauma effect using concepts such as alternate weaves (three-dimensional), special material coatings, or a "silly-putty-like" material whose resistance to loading increases with the rate at which the load is applied
- Increasing understanding of the medical factors which contribute to blunt trauma
- Establishing protective garment testing standards including an inexpensive human body simulator for evaluating penetration and blunt trauma parameters at the local departmental level.